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Final Technical Report
for
**Application of Aeroelastic Solvers Based on
Navier-Stokes Equations**

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Theo G. Keith, Jr.
Principal Investigator
Rakesh Srivastava
Co-Principal Investigator

Department of Mechanical, Industrial and Manufacturing Engineering
University of Toledo
Toledo, Ohio 43606

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Introduction

The propulsion element of the Advanced Subsonic Technology (AST) initiative of NASA is directed at increasing the overall efficiency of current aircraft engines. This effort implies increasing the efficiency of various components, such as fans, compressors, turbines etc. Using lighter material, larger diameter fans and higher pressure ratio compressors will increase the efficiency of the engines, but will also lead to more aeroelastic problems such as flutter or forced response. To address the aeroelastic problems, the Structural Dynamics Branch of NASA Lewis is involved in the development of numerical capabilities for analyzing the aeroelastic stability characteristics and forced response of wide chord fans, multi-stage compressors and turbines.

In order to design an engine to safely perform a set of desired tasks, accurate information of the stresses on the blade during the entire cycle of blade motion is required. This requirement in turn demands that accurate knowledge of steady and unsteady blade loading is available. To obtain the steady and unsteady aerodynamic forces for the complex flows around the engine components, for the flow regimes encountered by the rotor, an advanced compressible Navier-Stokes solver is needed. A finite volume based Navier-Stokes solver has been developed at Mississippi State University (MSU) for solving the flow field around multistage rotors. The focus of the research effort, under the cooperative agreement was on developing an aeroelastic analysis code (TURBO-AE) based on the Navier-Stokes solver developed by MSU. The TURBO-AE code has been developed for flutter analysis of turbomachine components and delivered to NASA and its industry partners. The code has been verified, validated and is being applied by NASA Lewis and by the aircraft engine manufacturers to analyze the aeroelastic stability characteristics of modern fans, compressors and turbines.

Aeroelastic analysis programs based on two and three-dimensional Euler equations are more efficient than an aeroelastic program based on Navier-Stokes equations, although the efficiency is obtained at the cost of loss of physics in the analysis. Nevertheless, these tools are effective in providing a reasonably accurate approximation of the characteristics for most

of the flight conditions of interest and as such are useful tools. Under this cooperative agreement effort was also devoted towards improving the capabilities of these tools.

Summary of Accomplishments

A pre-release version of the Navier-Stokes solver (TURBO) was obtained from MSU. Along with Dr. Milind Bakhle of the University of Toledo, subroutines for aeroelastic analysis were developed and added to the TURBO code to develop versions 1 and 2 of the TURBO-AE code. For specified mode shape, frequency and inter-blade phase angle the code calculates the work done by the fluid on the rotor for a prescribed sinusoidal motion. Positive work on the rotor indicates instability of the rotor. The version 1 of the code calculates the work for in-phase blade motions only. In version 2 of the code, the capability for analyzing all possible inter-blade phase angles, was added. The version 2 of TURBO-AE code was validated and delivered to NASA and the industry partners of the AST project. The capabilities and the features of the code are summarized in Refs. [1] & [2].

To release the version 2 of TURBO-AE, a workshop was organized at NASA Lewis, by Dr. Srivastava and Dr. M. A. Bakhle, both of the University of Toledo, in October of 1996 for the industry partners of NASA Lewis. The workshop provided the potential users of TURBO-AE, all the relevant information required in preparing the input data, executing the code, interpreting the results and bench marking the code on their computer systems. After the code was delivered to the industry partners, user support was also provided.

A new version of the Navier-Stokes solver (TURBO) was later released by MSU. This version had significant changes and upgrades over the previous version. This new version was merged with the TURBO-AE code. Also, new boundary conditions for 3-D unsteady non-reflecting boundaries, were developed by researchers from UTRC, Ref. [3]. Time was spent on understanding, familiarizing, executing and implementing the new boundary conditions into the TURBO-AE code.

Work was started on the phase lagged (time-shifted) boundary condition version (version 4) of the code. This will allow the users to calculate non-zero interblade phase angles using only one blade passage for analysis.

The capability of the ducted aeroelastic analysis code (DuctE3D) based on Euler equations was advanced by incorporating in it the aeroelastic analysis capability based on the eigenvalue analysis method and the work-per-cycle analysis method. To validate the eigenvalue analysis method it was applied to calculate the aeroelastic characteristics of a ducted fan geometry obtained by modifying an existing propfan geometry. The results obtained showed that the addition of a duct to this rotor made the unducted propfan dynamically unstable. These results are summarized in Ref. [4] and were presented at the 32nd Joint Propulsion conference held at Lake Buena Vista, Florida, July 1996. The DuctE3D code can also analyze the aeroelastic characteristics using the time domain analysis method. This provides an excellent tool to compare and contrast the capabilities and benefits of the three aeroelastic analysis methods. The three methods, time domain analysis, work-per-cycle analysis and eigenvalue analysis were applied to the same ducted rotor configuration to compare their relative merits. The results obtained, are summarized in Ref. [5] and were presented at the 33rd Joint Propulsion conference held at Seattle, Washington in July 1997.

The analysis capabilities of the two-dimensional multi-stage cascade aeroelastic code (MSAP-2D) were extended to solve for non-uniform upstream flow allowing for gust response analysis. Also, viscous terms were added to improve the physics of the analysis. The code was then applied to a linear cascade geometry to calculate the unsteady pressures on the cascade because of incoming gust. The results obtained are summarized in Ref. [6]. These tasks were accomplished in collaboration with Dr. T. S. R. Reddy of the University of Toledo.

User's manuals for the multi passage propfan aeroelastic code (Prop-3D) [7], the two-dimensional multi-stage cascade aeroelastic code (MSAP-2D) [8], and the multi passage aeroelastic code for ducted rotors (DuctE3D) [9] were published as NASA contractor reports.

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